

Assessing the response of dryland barley yield to climate variability in semi-arid regions, Iran

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Abstract: Precipitation and temperature are the most abiotic factors that greatly impact the yield of crop, particularly in dryland. Barley, as the main cereal is predominantly cultivated in dryland and the livelihood of smallholders depends on the production of this crop, particularly in arid and semi-arid regions. This study aimed to investigate the response of the grain yield of dryland barley to temperature and precipitation variations at annual, seasonal and monthly scales in seven counties of East and West Azerbaijan provinces in northwestern Iran during 1991–2010. Humidity index (HI) was calculated and its relationship with dryland barley yield was evaluated at annual and monthly scales. The results showed that the minimum, maximum and mean temperatures increased by 0.19°C/a, 0.11°C/a and 0.10°C/a, respectively, while annual precipitation decreased by 0.80 mm/a during 1991–2010. Climate in study area has become drier by 0.22/a in annual HI during the study period. Negative effects of increasing temperature on the grain yield of dryland barley were more severe than the positive effects of increasing precipitation. Besides, weather variations in April and May were related more to the grain yield of dryland barley than those in other months. The grain yield of dryland barley was more drastically affected by the variation of annual minimum temperature comparing with other weather variables. Furthermore, our findings illustrated that the grain yield of dryland barley increased by 0.01 t/hm² for each unit increase in annual HI during 1991–2010. Finally, any increase in the monthly HI led to crop yield improvement in the study area, particularly in the drier counties, i.e., Myaneh, Tabriz and Khoy in Iran.

Keywords: humidity index; crop yield; spatiotemporal variation; temperature; precipitation

1 Introduction

Barley (*Hordeum vulgare* L.) is one of the oldest cultivated crops in the world, growing at different latitudes from near the equator to 70° North (Dawson et al., 2015). Barley is naturally a drought-tolerant crop (Cammarano, 2019) and is also resistant to hot summers and cold winters with high variabilities in precipitation and temperatures (Brisson et al., 2010). Besides, barley has a significant contribution to international trade, and lack of adequate productions of this crop is accounted as one of the main factors of food scarcity worldwide (Fellmann et al., 2014; d'Amour et al., 2016). Accordingly, the livelihood of smallholders depends on barley production at national

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Received 2021-03-24; revised 2021-06-17; accepted 2021-08-13

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and regional scales, particularly in arid and semi-arid regions (Macdonald and Hall, 1980; Qader et al., 2018).

The arid and semi-arid regions have undergone changes including the increases in temperature and decreases in precipitation at annual, seasonal and monthly scales (Karimi et al., 2018; Rahimi et al., 2019; Senapati et al., 2019; Shirmohammadi et al., 2020; Kheiri et al., 2021). According to the latest reports, these climate changes significantly caused negative effects on crop productions (Chen et al., 2016; Bathiany et al., 2018; Bisbis et al., 2018). In this context, Schierhorn et al. (2020) investigated the impacts of climate change on wheat and barley yields in Kazakhstan. Their findings showed that the observed climate change led to both wheat and barley yield reduction by 1.9% and 4.8%, respectively. Hatfield et al. (2011) argued that cereal grain yields decreased between 4.1% and 10.0% with a 1°C increase in seasonal average temperature. Cammarano et al. (2019) evaluated the impacts of climate change on barley yield in the Mediterranean Basin and found that increasing air temperatures by 7%–18% and decreasing precipitation by 14%–21% led to 27% grain yield reduction in dryland. Asseng et al. (2011) found that a 2°C increases in average temperature during the growing season reduced the wheat yield by 50%. Xiao et al. (2016) reported that rainfed wheat yield decreased significantly by 19.5%, 33.6% and 53.1%, respectively for 10%, 20% and 30% decreases in precipitation. Identifying the crop yields sensitivity to climate change is of high importance for the adoption of effective and adaptive strategies (Zhao et al., 2017), which improves the yield potentials.

Arid and semi-arid region covers an area of about 1.75×10^6 km² in Iran. Temperature varies from –20°C to 50°C, while annual precipitation varies from less than 50 to more than 1000 mm in Iran (Mesgaran et al., 2017). Iran is a predominantly agricultural country and arable lands are approximately 37×10^6 hm² (Karimi et al., 2018). Cereals are known as the most important crops cultivated in arable lands of Iran and barley is among the main cereals mostly cultivated in drylands. Furthermore, barley provides both animal and human food, and the livelihood of local farmers is strongly influenced by the production of this crop. Barley is the second dryland crop of the country in terms of the majority of cropping area that contributes to almost 18% of the total dryland agricultural products (Ministry of Agriculture-Jihad (MAJ), 2018). Almost 60% of this area is dryland where barley production completely depends on the amounts of precipitation during the crop growing season.

East Azerbaijan and West Azerbaijan, located in the northwest Iran are among the two main provinces in terms of barley production, which together produce 10% of the total dryland barley in Iran (MAJ, 2018). Thus, the present study aims to (1) assess the time-series of temperature and precipitation variability in East and West Azerbaijan provinces during 1991–2010; and (2) investigate the relationship between the variability in temperature and precipitation with dryland barley yield. Accordingly, this study seeks to answer the following research questions: Which variables (precipitation and/or temperature) changed more drastically during the study period? Which areas have experienced more changes in the grain yield of dryland barley during the study period? Which climatic variables have affected the grain yield of dryland barley? And when are the most critical times in determining the grain yield of dryland barley?

2 Materials and methods

2.1 Study area

Two northwestern provinces of Iran (i.e., East Azerbaijan and West Azerbaijan) are chosen as the study area (Fig. 1). East Azerbaijan Province covers an area of 45,481 km², consisting of approximately 2.8% of the total area of Iran. Mean annual precipitation is 288.9 mm and annual minimum, maximum and mean temperatures are 6.9°C, 18.0°C and 12.4°C, respectively in East Azerbaijan Province. West Azerbaijan Province covers an area of 37,059 km², consisting approximately 2.3% of the total area of Iran. Mean annual precipitation is 341.0 mm and annual minimum, maximum and mean temperatures are 5.4°C, 17.6°C and 11.5°C, respectively in West Azerbaijan Province. There are seven counties (i.e., Ahar, Tabriz, Maragheh, Myaneh, Urmia, Khoy and Makou) in these two provinces (Fig. 1).

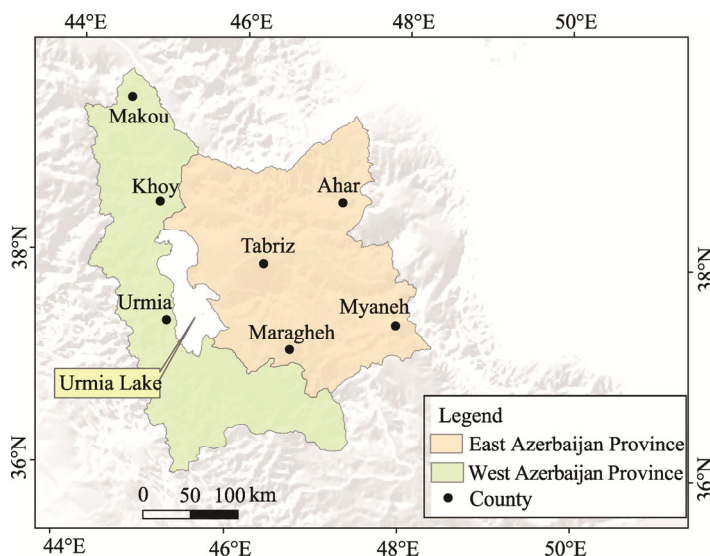


Fig. 1 Location of the seven counties in the East and West Azerbaijan provinces, Iran

2.2 Weather data

Weather data were collected from weather stations of Iran Meteorological Organization. Weather data included annual minimum, maximum and mean temperatures and the total precipitation during 1991–2010. Before using the weather data for analysis, we applied the outlier detection test to exclude outliers and the normality test to evaluate the homogeneity of the data. All data were averaged to obtain their corresponding values at annual, seasonal and monthly scales.

2.3 Crop yield data

Yield data of dryland barley during 1991–2010 were collected from the MAJ, Iran. The sowing date of barley mainly depends on the precipitation in fall and the harvesting time also depends on air temperature around the late-spring or early-summer. Therefore, barley production in dryland is totally affected by local climate. To determine the growing season of barley in each province, we had a meeting with agronomists in East and West Azerbaijan Agricultural Organizations. The growing season of barley in both provinces almost overlapped, and the beginning and end of the growing season were considered as July and October, respectively. It should be noted that the purpose of this study is to investigate the impacts of weather variables on the grain yield of dryland barley during the crop growing season in July and October. Therefore, the correlations between the weather variables and the crop yield were not considered in the analysis from August to September.

Given that the objective of this study was to investigate the effects of climate factors (i.e. temperature and precipitation) on the grain yield of dryland barley, the impact of any non-climatic factors such as crop genetic and technical improvements were eliminated by the Double Exponential Smoothing (DES) method (Joseph and LaViola, 2003). According to the current method, we calculated the crop yield anomalies as the difference between the yield in each year and the average of observed long-term yield (Fig. 2). Also, compared with other approaches, DES generates new observations with relatively more weight than the older observations (Bannayan et al., 2010). However, it should be noted that this method does not entirely eliminate the impacts of non-climatic factors across the years, but it is the best possible way to exclude the impacts of other factors (Kheiri et al., 2017).

2.4 Humidity index (HI)

In this study, we used the de Martonne equation as below to quantify the HI of all the studied counties (Bannayan et al., 2010; Zarghami et al., 2011):

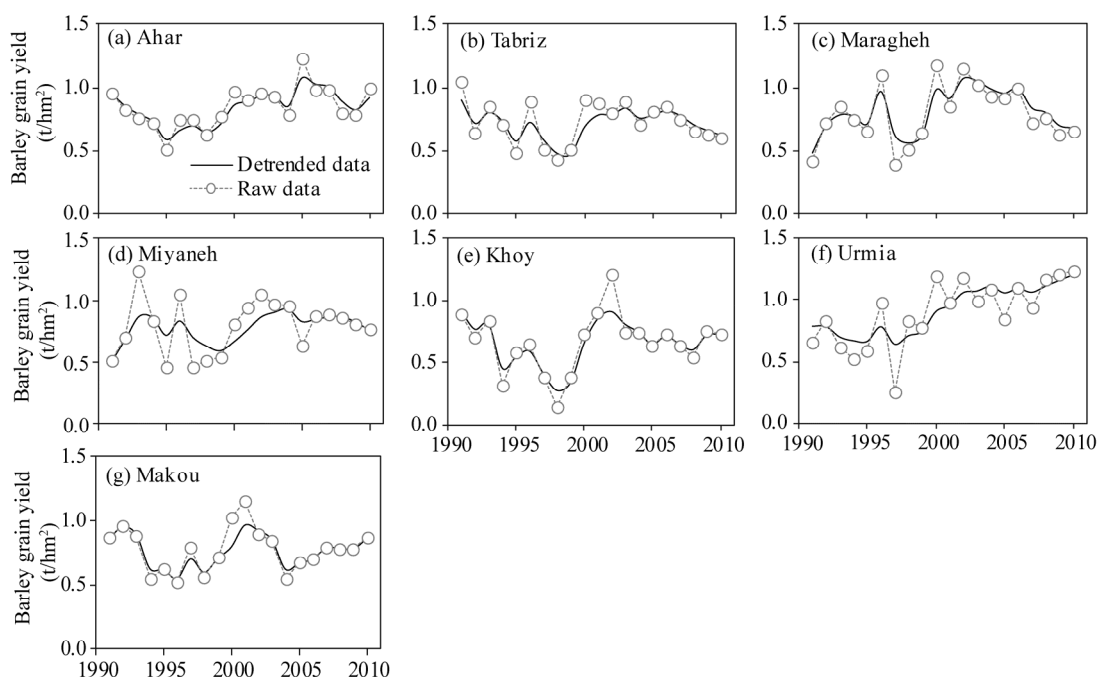


Fig. 2 Time trends of raw (dashed line) and detrended (solid line) barley grain yield in the seven counties during 1991–2010

$$HI = \frac{P}{T + 10} \begin{cases} \text{semi-arid if } 10 \leq HI < 20 \\ \text{arid if } HI < 10 \end{cases}, \quad (1)$$

where P is the mean annual/monthly precipitation (mm); and T is the annual/monthly mean temperature ($^{\circ}\text{C}$). When HI falls in the range between 10 and 20, the climate is classified as semi-arid. HI less than 10 refers to the arid climate (Croitoru et al., 2013).

2.5 Statistical analysis

In this study, a simple linear regression was used to investigate the variation of each variable at annual/seasonal/monthly scale during 1991–2010. Pearson correlation was calculated at annual, seasonal, and monthly scales to investigate the relationships between the weather variables and HI with the grain yield of dryland barley. Using Minitab software, we calculated simple linear regression and Pearson correlation. In the next step, the spatial analysis of weather variables, HI and barley yield were done using ArcGIS10.4 (ESRI, 2016) and through the Inverse Distance Weighting (IDW) interpolation method. IDW, as the deterministic spatial interpolation model, is one of the most popular and frequently used forms of interpolation adopted by geographers and geoscientists to interpolate climate variables (Chen and Liu, 2012; Yang et al., 2015; Jeong et al., 2020). Simplicity of calculation, ease of understanding and high output efficiency are the main advantages of IDW method (Maleika, 2020).

3 Results

3.1 Spatiotemporal variations of the grain yield of barley, climate variables and annual HI

The spatial distribution indicated that the highest grain yield of barley was observed in Urmia and Ahar counties with more than 0.80 t/hm^2 , while the lowest grain yield of barley belonged to Khoy and Tabriz counties with less than 0.70 t/hm^2 (Fig. 3a). According to the results of Table 1, on average, the grain yield of dryland barley showed an ascending slope by $0.01 \text{ t/(hm}^2\cdot\text{a)}$ in the study area during 1991–2010. For instance, the grain yield of dryland barley significantly increased by 0.01 and $0.03 \text{ t/(hm}^2\cdot\text{a)}$ in Ahar and Urmia counties, respectively during the study period (Table 1).

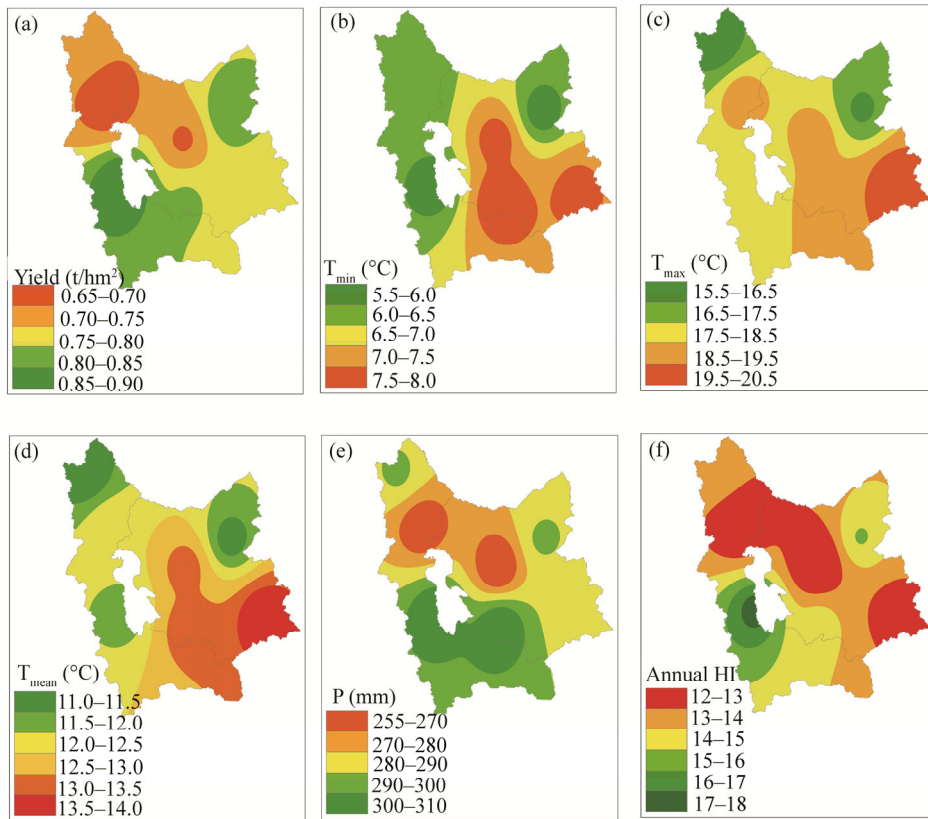


Fig. 3 Spatial distribution of barley grain yield (a), weather variables (b–e) and annual HI (f) in the seven counties during 1991–2010. T_{min}, annual minimum temperature; T_{max}, annual maximum temperature; T_{mean}, annual mean temperature; P, precipitation; HI, humidity index.

There was large variability within the spatial distribution of each weather variable in the study area (Fig. 3). In this regard, the spatial distributions of annual minimum, maximum and mean temperatures showed that Ahar, Urmia, and Makou counties were cooler than other counties, whilst Myaneh County was the hottest during 1991–2010 (Fig. b–d). The total precipitation ranged from 255 to 310 mm in the study area (Fig. 3e). Accordingly, Tabriz and Khoy counties had the lowest annual precipitation, while the highest precipitations were observed in Urmia and Maragheh counties, respectively. In general, East Azerbaijan experienced higher air temperatures and lower precipitation than West Azerbaijan during 1991–2010 (Fig. 3). Table 1 shows that annual minimum, maximum and mean temperatures increased by 0.19°C/a, 0.11°C/a, and 0.10°C/a, respectively during 1991–2010. The highest and the strongest variations in air temperature were observed in Myaneh County (Table 1). On average, total precipitation decreased by –0.80 mm/a during 1991–2010. Besides, the most impressive variation in the total precipitation was obtained in Myaneh County, with a decrease of 5.48 mm/a.

According to annual HI distribution, we classified all of the studied counties as semi-arid climate (Eq. 1; Fig. 3f). However, Khoy, Tabriz, and Myaneh counties with annual HI<13, were drier, while Urmia County with annual HI>17, was wetter than other counties during the study period (Fig. 3f). The regression analysis indicated that the climate of the study area was changing to a drier with, on average, 0.22/a reduction in annual HI during 1991–2010 (Table 1). In addition, annual HI showed a more significant descending trend in East Azerbaijan than in West Azerbaijan during the study period. However, the most significant reduction in annual HI was detected in Myaneh County with a decrease of 0.40 per year over the study period (Table 1).

Table 1 Slope of regression coefficient of the climate variables, annual HI and barley grain yield during 1991–2010

County	T _{min} (°C)	T _{max} (°C)	T _{mean} (°C)	Precipitation (mm)	Annual HI	Barley grain yield (t/hm ²)
Ahar	0.03*	0.06**	0.04*	1.47	-0.17	0.01*
Tabriz	0.11*	0.14**	0.13**	-0.35	-0.15*	-0.01
Maragheh	0.16**	0.18**	0.17**	-1.52	-0.20*	0.02
Myaneh	0.15**	0.20**	0.18**	-5.48**	-0.40*	0.01
Urmia	0.01	0.08*	0.04*	2.20	-0.42	0.03**
Khoy	0.86	0.06**	0.08*	-0.07**	-0.11	0.00
Makou	0.04*	0.06*	0.05*	-1.86	-0.08	0.01

Note: T_{min}, annual minimum temperature; T_{max}, annual maximum temperature; T_{mean}, annual mean temperature. * and ** indicate significances at $P<0.05$ and $P<0.01$ levels, respectively.

3.2 Relationship between weather variables and grain yield of barley at annual, seasonal and monthly scales

The correlation analysis showed the negative impacts of increasing air temperature on the grain yield of dryland barley in some counties at annual scale (Table 2). In this regard, with an increase in annual minimum temperature, the grain yield of dryland barley decreased significantly in Makou ($r = -0.54$). Furthermore, the grain yield of dryland barley is significantly decreased by increasing the annual maximum temperature in Urmia and Makou ($r = -0.53$ and $r = -0.54$, respectively). In addition, there was a negative relationship between annual mean temperature and grain yield of barley in Makou ($r = -0.54$; Table 2). However, the results of Table 2 indicated no significant correlation between precipitation and grain yield of barley at annual scale during 1991–2010.

Table 2 Analysis of correlations between weather variables and barley grain yield at annual scale during 1991–2010

County	T _{min} -yield		T _{max} -yield		T _{mean} -yield		Precipitation-yield	
	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value
Ahar	-0.22	0.44	-0.21	0.45	-0.22	0.44	-0.22	0.42
Tabriz	-0.43	0.11	-0.47	0.08	-0.46	0.09	0.11	0.70
Maraghe	-0.26	0.36	-0.17	0.54	-0.21	0.46	-0.24	0.39
Myaneh	-0.39	0.15	-0.49	0.06	-0.46	0.08	0.43	0.11
Urmia	0.39	0.15	-0.53	0.04	0.47	0.07	-0.29	0.29
Khoy	-0.28	0.31	-0.31	0.26	-0.33	0.23	0.26	0.34
Makou	-0.54	0.04	-0.54	0.04	-0.54	0.04	-0.15	0.60

Note: T_{min}, annual minimum temperature; T_{max}, annual maximum temperature; T_{mean}, annual mean temperature.

According to the correlation analysis at the seasonal scale, we observed significantly negative relationships of the minimum, maximum and mean temperatures in winter with grain yield of barley in Myaneh ($r = -0.62$, $r = -0.63$ and $r = -0.63$, respectively) (Table 3). In spring, an increase in the maximum temperature significantly decreased the grain yield of dryland barley in Khoy ($r = -0.53$) (Table 3). Also, the relationship between the precipitation in spring and the grain yield of dryland barley was statistically significant in Myaneh ($r = 0.52$). In addition, an increase in the minimum, maximum and mean temperatures in this season had a negative impact on the grain yield of dryland barley in Myaneh ($r = -0.72$, $r = -0.59$ and $r = -0.65$, respectively) (Table 3). In fall, an increase in the minimum and mean temperatures significantly decreased the grain yield of dryland barley in Maragheh ($r = -0.58$ and $r = -0.54$, respectively) (Table 3). Although there were remarkable relationships between weather variables and grain yield in the other counties at seasonal scale, these relationships were not statistically significant.

Table 3 Analysis of correlations between weather variables and barley grain yield at seasonal scale during 1991–2010

County	Season	T _{min} –yield		T _{max} –yield		T _{mean} –yield		Precipitation–yield	
		<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value	<i>r</i>	<i>P</i> -value
Ahar	Winter	−0.15	0.59	−0.13	0.66	−0.14	0.63	0.09	0.74
	Spring	−0.33	0.23	−0.31	0.26	−0.33	0.23	0.17	0.55
	Summer	−0.14	0.61	−0.01	0.98	−0.06	0.83	−0.37	0.17
	Fall	−0.02	0.93	−0.11	0.69	−0.08	0.78	0.09	0.76
Tabriz	Winter	−0.26	0.34	−0.33	0.23	−0.30	0.27	−0.01	0.98
	Spring	−0.48	0.07	−0.45	0.09	−0.47	0.08	0.15	0.65
	Summer	−0.25	0.37	−0.04	0.90	−0.14	0.61	0.40	0.14
	Fall	−0.27	0.34	−0.38	0.16	−0.35	0.20	0.17	0.51
Maragheh	Winter	0.05	0.86	0.01	0.98	0.03	0.93	−0.07	0.81
	Spring	−0.40	0.14	−0.21	0.46	−0.29	0.30	0.13	0.65
	Summer	0.09	0.76	0.32	0.25	0.21	0.21	0.34	0.22
	Fall	−0.58	0.03	−0.50	0.06	−0.54	0.04	0.36	0.19
Myaneh	Winter	−0.62	0.01	−0.63	0.01	−0.63	0.01	0.16	0.58
	Spring	−0.72	0.00	−0.59	0.02	−0.65	0.01	0.52	0.04
	Summer	−0.03	0.93	−0.22	0.43	−0.14	0.62	−0.48	0.07
	Fall	−0.44	0.10	−0.25	0.37	−0.36	0.19	0.47	0.08
Urmia	Winter	−0.02	0.93	0.24	0.38	0.22	0.44	−0.23	0.41
	Spring	−0.25	0.37	−0.22	0.42	−0.23	0.40	0.46	0.08
	Summer	0.15	0.59	0.48	0.07	0.39	0.15	−0.32	0.25
	Fall	−0.36	0.19	−0.48	0.07	−0.48	0.07	−0.10	0.73
Khoy	Winter	−0.20	0.48	−0.10	0.73	−0.15	0.60	0.35	0.21
	Spring	−0.18	0.53	−0.53	0.04	−0.35	0.20	−0.16	0.57
	Summer	−0.09	0.74	0.21	0.45	0.07	0.81	−0.20	0.49
	Fall	−0.45	0.09	−0.49	0.07	−0.50	0.06	0.50	0.06
Makou	Winter	−0.39	0.16	−0.29	0.29	−0.35	0.21	0.30	0.28
	Spring	−0.44	0.10	−0.29	0.30	−0.36	0.19	0.19	0.18
	Summer	−0.02	0.95	0.03	0.91	0.02	0.96	−0.30	0.29
	Fall	−0.30	0.28	−0.30	0.22	−0.30	0.27	0.23	0.42

Note: T_{min}, seasonal minimum temperature; T_{max}, seasonal maximum temperature; T_{mean}, seasonal mean temperature.

Table 4 shows the results of correlation analysis between monthly weather variables and grain yield of barley in the study area during 1991–2010. In January, the minimum and mean temperatures indicated significantly negative relationships with the grain yield of dryland barley in Makou ($r = -0.54$ and $r = -0.53$, respectively). Although significant correlations were observed, it could not be a desired result for describing the correlation of the minimum and maximum temperatures with the grain yield of dryland barley in Makou in January. Makou has very cold and freezing weather in winter (e.g., January) and the frost damage is known as one of the major stressors of barley cultivation in this area. Therefore, it seems that an increase in temperature could lead to positive impacts of crop yield. In April, the minimum, maximum and mean temperatures were negatively related to the grain yield of dryland barley in Myaneh with the correlation coefficients of -0.54 , -0.56 , and -0.59 , respectively. In addition, the relationship between precipitation and the grain yield of dryland barley in April was positively significant in Myaneh ($r = 0.55$). In May, the minimum, maximum and mean temperatures showed negatively significant relationships with the grain yield of dryland barley in Ahar ($r = -0.55$, $r = -0.52$ and $r =$

−0.58, respectively). Also, the increased minimum and mean temperatures in this month significantly decreased the grain yield with the correlation coefficients of −0.60 and −0.54 in Tabriz, −0.57 and −0.54 in Myaneh, and −0.76 and −0.58 in Makou, respectively (Table 4). In June, the minimum temperature showed a significant and negative correlation with the grain yield of dryland barley in Myaneh ($r = -0.61$). In December, an increase in the mean temperature significantly decreased the grain yield of dryland barley in Myaneh ($r = -0.57$). Furthermore, the precipitation of this month showed a significant and positive relationship with the grain yield of dryland barley in Tabriz ($r = 0.60$; Table 4).

Table 4 Analysis of correlations between weather variables and barley grain yield at monthly scale during 1991–2010

County	Variable	Month									
		Jan	Feb	Mar	Apr	May	Jun	Jul	Oct	Nov	Dec
Ahar	T _{min}	−0.34	0.00	−0.01	−0.09	−0.55*	−0.12	−0.09	0.33	0.10	−0.28
	T _{max}	−0.27	−0.05	−0.05	−0.16	−0.52*	−0.02	0.18	0.18	0.10	−0.40
	T _{mean}	−0.31	−0.03	−0.03	−0.14	−0.58*	−0.05	0.11	0.26	0.10	−0.35
	P	−0.25	0.03	0.22	−0.20	0.00	−0.14	−0.16	−0.13	0.00	0.35
Tabriz	T _{min}	−0.49	−0.09	−0.09	−0.13	−0.60**	−0.47	−0.07	0.03	−0.07	−0.29
	T _{max}	−0.46	−0.23	−0.22	−0.25	−0.49	−0.37	0.16	−0.02	−0.09	−0.48
	T _{mean}	−0.49	−0.17	−0.17	−0.20	−0.54*	−0.42	0.05	0.00	−0.09	−0.40
	P	−0.19	0.05	0.10	0.13	−0.00	0.20	−0.01	−0.29	0.05	0.60**
Maragheh	T _{min}	−0.12	0.10	0.14	−0.21	−0.31	−0.46	0.29	−0.38	−0.05	−0.43
	T _{max}	−0.14	−0.03	0.14	−0.31	−0.14	−0.08	0.39	−0.36	0.08	−0.44
	T _{mean}	−0.13	0.03	0.14	−0.27	−0.21	−0.25	0.35	−0.37	0.04	−0.43
	P	0.04	0.30	−0.42	0.30	0.01	−0.22	−0.38	0.23	−0.44	0.22
Myaneh	T _{min}	−0.16	0.14	0.05	−0.54*	−0.57*	−0.61**	−0.03	−0.07	0.01	−0.58
	T _{max}	−0.30	−0.16	−0.13	−0.56*	−0.50	−0.39	−0.06	−0.11	−0.05	−0.48
	T _{mean}	−0.23	−0.04	−0.07	−0.59*	−0.54*	−0.50	−0.05	−0.10	−0.03	−0.57*
	P	−0.09	0.16	0.21	0.55*	0.11	−0.05	−0.23	0.35	0.28	0.29
Urmia	T _{min}	−0.08	0.26	0.33	0.23	0.04	0.36	0.42	0.44	−0.03	−0.07
	T _{max}	−0.01	0.24	0.35	−0.03	0.10	0.43	0.46	0.36	0.12	−0.13
	T _{mean}	−0.05	0.25	0.35	0.02	0.09	0.41	0.49	0.44	0.08	−0.11
	P	−0.30	−0.07	−0.09	−0.35	−0.18	−0.43	−0.42	0.01	−0.30	0.29
Khoy	T _{min}	−0.49	0.03	0.08	−0.15	−0.10	−0.29	−0.12	0.06	−0.39	−0.32
	T _{max}	−0.41	0.05	0.10	−0.40	−0.38	−0.16	0.26	−0.04	−0.29	−0.48
	T _{mean}	−0.47	0.04	0.10	−0.31	−0.18	−0.22	0.10	0.01	−0.35	−0.42
	P	−0.14	0.30	0.28	0.14	−0.18	−0.30	−0.12	0.39	0.30	0.44
Makou	T _{min}	−0.54*	−0.24	−0.21	−0.09	−0.76**	−0.27	0.14	−0.14	−0.36	−0.13
	T _{max}	−0.51	−0.17	−0.10	−0.11	−0.44	−0.08	0.19	−0.12	−0.18	−0.28
	T _{mean}	−0.53*	−0.21	−0.15	−0.10	−0.58*	−0.16	0.17	−0.11	−0.18	−0.20
	P	0.50	0.19	0.01	−0.10	−0.47	−0.18	−0.38	−0.23	0.08	−0.20

Note: T_{min}, monthly minimum temperature; T_{max}, monthly maximum temperature; T_{mean}, monthly mean temperature; P, precipitation. * and ** indicate significances at $P < 0.05$ and $P < 0.01$ levels, respectively.

4 Discussion

4.1 Spatiotemporal relationships of barley grain yield, weather variables with annual HI

The findings of this study showed considerable similarities between the spatial distributions of

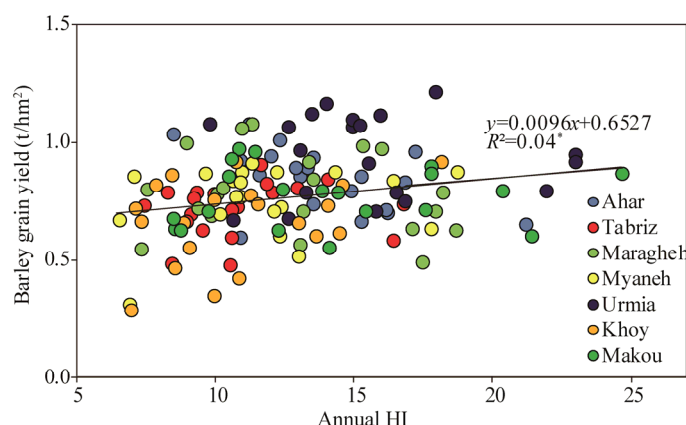


Fig. 4 Scattered plot of association between barley grain yield and annual HI (humidity index) in the seven counties during 1991–2010. * indicates significance at $P < 0.05$ level.

Table 5 Analysis of correlations between HI and barley grain yield at monthly scale during 1991–2010

Month	County						
	Ahar	Tabriz	Maragheh	Myaneh	Urmia	Khoy	Makou
Jan	−0.01	−0.04	0.10	−0.04	−0.24	0.21	0.53*
Feb	−0.04	−0.02	0.25	0.02	−0.18	0.23	0.19
Mar	0.26	0.11	−0.39	0.23	−0.20	0.26	0.03
Apr	−0.14	0.16	0.32	0.53*	−0.28	0.21	−0.06
May	0.44	0.45	0.56*	0.68**	−0.11	−0.11	−0.36
Jun	−0.12	0.21	−0.22	−0.03	−0.42	−0.28	−0.15
Jul	−0.13	−0.02	−0.38	−0.23	0.40	−0.12	−0.38
Oct	−0.14	−0.28	0.41	0.37	−0.01	0.38	−0.23
Nov	−0.03	0.06	−0.45	0.29	−0.31	0.30	0.10
Dec	0.53*	0.66**	0.24	0.31	0.26	0.64**	0.29

Note: * and ** indicate significances at $P < 0.05$ and $P < 0.01$ levels, respectively.

annual HI and total precipitation revealing the higher contribution of the total precipitation in determining annual HI (Fig. 3e and f). Also, our findings illustrated the strong similarities between annual HI and grain yield of barley (Fig. 3a and f). Accordingly, it could be concluded that in the areas with a higher annual HI, more grain yield is expected. These findings are in line with Bannayan et al. (2010) and Kheiri et al. (2017), who indicated that annual HI quite closely followed a spatial distribution of total precipitation. They also reported that wheat and barley yield distributions have been impressively influenced by the spatial distribution of annual HI, which emphasizes the undeniable role of annual HI in determining the crop yield in an area. We found that climate of the study area tended to be drier (the temperature increased and the precipitation decreased), particularly in drier areas (e.g., Myaneh and Khoy) during 1991–2010 (Table 1). The current findings confirmed the reports of Tabari et al. (2014), who focused on the effects of climate on the de Martonne aridity index in Iran during 1966–2005 and found that the climate in the northwest of Iran had significantly become drier.

4.2 Assessment of barley grain yield response to weather variables at annual, seasonal and monthly scales

At annual scale, we found that the grain yield of dryland barley is negatively affected by the increased air temperature. Higher temperatures not only accelerate the onset of phenological stages but also shorten the duration of growth, which leads to reduced light interception for lower rates of photosynthesis and leaf area, or even a withering of leaves, and consequently the

reductions in biomass and grain yield (Asseng et al., 2015). According to the reports of Bannayan et al. (2010), air temperature was a determining factor in dryland wheat and barley grain yields in the semi-arid regions of Khorasan Province in the northeastern Iran. Also, Alexandrov and Hoogenboom (2001), Padakandla (2016) and Kheiri et al. (2021) have reported that an increase in ambient temperatures results in shortening the length of crop growth and consequently reducing the final grain yield.

At seasonal scale, we reached two main findings: (1) the negative effects of increasing temperature on the grain yield of dryland barley were more severe and more significant than the positive effects of increasing precipitation, particularly in drier areas (e.g., Myaneh); and (2) comparing with other seasons, the weather variations in spring were related more to the grain yield of dryland barley. These findings were supported with the results of the relationships between weather variables and grain yield of dryland barley at month scale, where April and May were detected as the most important months in which the weather variations had stronger and more substantial relationships with the grain yield of dryland barley. The effects of seasonal or monthly weather variations on grain yield are mainly due to different hydrothermal demand of crop in different growing seasons. In this regard, when hydrothermal conditions are in sync with crop growth requirements, grain yield can be increased, and vice versa. It should be highlighted that obtaining proper grain yield is relevant to the aggregation of the materials during the crop growing season and the transmission of dry matter to grain during the reproductive phase. As the reproductive phase in barley starts in spring, approximately between April and May throughout the study area, an increase in temperature could advance the leaves senescence, decrease the amount of radiation that the crop canopy intercepts, and lead to the grain yield reduction during this period. Siebert and Ewert (2014) presented that at sensitive growing seasons, such as the grain-filling period (reproductive phase), high temperatures can disrupt pollination, reduce the number of grains formed, and thus reduce the final yield dramatically. Rosenzweig et al. (1996) indicated that the higher temperatures in late-spring, which coincides with the grain-filling period, increase maintenance respiration, reduce CO_2 assimilation rate and lead to the negative consequences on yield. In other studies, similar findings have also been reported (Tewolde et al., 2006; Tao et al., 2015; Chen et al., 2017; Kheiri et al., 2017; Karimi et al., 2018). In this context, previous studies suggested that the adaptation strategies, such as changes in sowing dates and cultivars, should be taken into account to mitigate the negative effects of increased temperature (Plaut et al., 2004; Ugarte et al., 2007; Kheiri et al., 2021).

The findings of this study also showed the positive impacts of precipitation in spring (e.g., April) on grain yield of dryland barley in the drier area (i.e., Myaneh). It was reported that enough precipitation during reproductive phase, can postpone the leaf senescence by neutralization of terminal drought, as the most prominent concern in dryland production, which causes chlorophyll and membrane breakdown and leaves chloroses (Farooq et al., 2014), thus leading to an increased grain yield (Lobell et al., 2011; Nio et al., 2011; Tao et al., 2017). We found that relationships between crop yield and weather variables could be attributed to the negative impacts of minimum temperature (Table 4). This finding is in agreement with the results of Lizaso et al. (2018), Xiao et al. (2018) and Kheiri et al. (2021), who found that warmer night temperatures cause enhanced maintenance respiration that can be at the expense of decreasing crop growth and grain yield.

4.3 Assessment of barley grain yield response to HI at annual and monthly scales

As indicated in Figure 4, the grain yield positively responded to the increase of annual HI when all the study areas were considered. This finding confirms our results illustrated in Figure 3 and revealed strong similarities between annual HI and grain yield. These results describe that annual HI was able to justify the temporal and spatial changes of rainfed barley in the study area. In other words, the calculation of annual HI can be an appropriate and simple representative to determine which areas are suitable for growing dryland crops such as barley in terms of climate (precipitation and temperature) condition.

The findings of this study illustrated that any increase in monthly HI led to crop yield improvement in the study area, particularly in drier counties (e.g., Myaneh, Tabriz and Khoy).

Furthermore, the correlation between grain yield of dryland barley and monthly HI during former growing season (April–July) was stronger than later growing season (October–March). Experience of local farmers have shown that the most crucial times of barley growth and development occur at latter growing season, and drought stress in this period affects crop yield more than former growing season. Narasimhan and Srinivasan (2005) found that a strong relationship between drought indices and wheat yield was observed during the growing season, and adequate soil moisture during the growing season would be critical for the final grain yield. In another study, Bannayan et al. (2010) divided the growing seasons of barley and wheat into two parts, i.e., wet (early to the middle of the growing season) and dry (end of the growing season) seasons and found a stronger relationship between HI and crop in the dry season. They confirmed that the higher monthly HI during the dry season is more effective to crop yield. Generally, it can be noted that HI was an appropriate index to describe the spatiotemporal variability of grain yield dryland barley across different counties in Iran.

5 Conclusions

This study investigated the grain yield of dryland barley response to temperature and precipitation variations at annual, seasonal and monthly scales. The findings of this study showed that the climate of the study area tended to be drier, particularly in drier areas during 1991–2010 (e.g., Myaneh and Khoy). The negative effects of increasing temperature on grain yield of dryland barley were more severe and significant than the positive effects of increasing precipitation, especially in drier areas. In addition, weather variations in the spring (April and May) were more closely linked to grain yield. The results also revealed that in comparison with other weather variables, annual minimum temperature variations had a greater impact on grain yield. Furthermore, we found that grain yield distribution has been impressively influenced by the spatial distribution of annual HI, highlighting the undeniable role of annual HI in determining the crop yield in an area. Overall, we found that any increase in monthly HI led to grain yield improvement in the study area, particularly in drier counties. The main implication of the study's findings is to better understand crop–climate relationships during the crop growing season. The findings of this study can be applied to regional yield forecasting as well as the projections of climate variability impacts on yield of dryland crops.

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